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14. ABSTRACT
Near-field plates and their potential uses were theoretically and experimentally investigated under this grant. Near-field plates are subwavelength-textured surfaces that can focus electromagnetic fields to deep subwavelength resolutions. Their operation was theoretically explained, design methodologies were formulated, and several prototypes developed at microwave frequencies. This research effort also included a second objective. The second objective was rather broad: to arbitrarily control electromagnetic fields within a 2D region of space using anisotropic and inhomogeneous metamaterials. This effort involved the development of circuit-based metamaterials that exhibit tensorial effective material parameters, and the implementation of electromagnetic devices using such metamaterials. It also involved the development of synthesis methods for anisotropic and inhomogeneous two dimentional (2D) metamaterials.

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I. OBJECTIVES

The primary objective of the proposed work was to theoretically and experimentally investigate near-field plates and their potential uses. Near-field plates are subwavelength-textured surfaces that can focus electromagnetic fields to deep subwavelength resolutions. Their operation was theoretically explained, design methodologies were formulated, and various prototypes developed at microwave frequencies.

A second objective also emerged during the course of this research work. The second objective was rather broad: to arbitrarily control electromagnetic fields within a 2D region of space using anisotropic and inhomogeneous metamaterials. This effort involved the development of circuit-based metamaterials that exhibit tensorial effective material parameters, and the implementation of electromagnetic devices using such metamaterials. It also included the development of synthesis methods for anisotropic and inhomogeneous 2D metamaterials.

II. NEAR-FIELD PLATES

This section describes research work related to the primary objective of developing near-field plates: textured surfaces that allow subwavelength control over the electromagnetic near field.

A. Background on Near-Field Plates

During the past decade, there has been strong interest in the development and characterization of electromagnetic metamaterials, as well as their practical application. Metamaterials are materials engineered at a subwavelength scale to exhibit tailored electromagnetic properties. Their electromagnetic properties are derived from their subwavelength structure/granularity, rather than solely their constitutive materials. Interest in metamaterials surged with the development of a metamaterial exhibiting a negative index of refraction [1] in 2001. One of the first metamaterial devices that intrigued the scientific community and drew widespread attention was the "perfect lens" introduced by John B. Pendry in [2]. This seminal work set off the scientific and engineering community's quest for the superlens: a lens capable of subwavelength resolution [3]. A superlens is a slab with negative material parameters (negative permittivity and permeability) that can manipulate the near field and focus electromagnetic waves to resolutions beyond the diffraction limit. Since Pendry's theoretical proposal [2], numerous superlenses have been implemented at frequencies ranging from the radio frequency (RF) to the optical spectrum [4–8].

An alternative approach to subwavelength focusing was introduced by the PI and his collaborator Roberto Merlin in 2007 [9, 10], and experimentally verified in 2008 [11]. This new approach relies on subwavelength-structured, grating-like surfaces rather than volumetric structures (slabs). These devices have been referred to by a number of names including near-field plates [9–16] and evanescent field lenses [9], and later as holographic screens [17], metascreens [18] and spatially beam shifted transmission screens [19]. In this report, they will be collectively referred to as near-field plates. These planar structures can focus electromagnetic waves beyond the diffraction limit, but are simpler to fabricate than the volumetric metamaterial superlenses. They do not require 3D fabrication, but rather only single layer processing.

Near-field plates can be viewed as metamaterial surfaces (metasurfaces or metafilms) [20]. They are textured/structured at a subwavelength scale, in the same way that volumetric metamaterials exhibit subwavelength granularity. They can be described macroscopically in terms of effective impedances, just as volumetric metamaterials are described in terms of effective material parameters: permittivity and permeability. In the most general sense, a near-field plate is a collection/array of closely spaced, non-periodically varying scatterers (polarizable particles, impedance elements, small antennas) that, when excited, strongly interact to produce a desired subwavelength focal pattern. A near-field plate can take on various forms. It can be a non-periodic surface or array of polarizable particles that is excited by an incident field [10–12, 18, 19], a directly fed array of subwavelength antennas, or a driven subwavelength antenna element surrounded by parasitic radiators [13–15, 21–23]. In all these cases, a highly oscillatory field is excited at the surface of the near-field plate which converges to a subwavelength pattern at a near-field focal distance [24].

Antenna engineers typically deal with wireless systems that operate at large distances, and therefore contend with far-field radiation and pattern synthesis. The near field of an antenna is generally considered a nuisance that causes undesired effects such as mutual coupling between antenna elements or interactions with the platform onto which the antenna is mounted. In contrast, near-field microscopists deal with length scales at the other extreme; those that are subwavelength. In near-field microscopy, subwavelength focal spots or field patterns, needed for high-resolution imaging, are produced by placing subwavelength probes (tapered waveguide apertures, dielectric and metallic tips) in close proximity to the sample being imaged [25, 26]. In this way, detection over a subwavelength area of the sample is achieved. In near-field plate design, pattern synthesis techniques are applied at a near-field operating distance. So length scales are close to those in near-field microscopy, but the design techniques are reminiscent of those employed in antenna design.

Near-field plates provide some distinct advantages over conventional probes used to confine/localize electromagnetic field to subwavelength spots, such as the electrically small apertures used in near-field microscopy [25]. Firstly, the shape of the subwavelength focal pattern can be tailored by simply changing the design of the plate. In other words, near-field plates allow one to manipulate and sculpt the electromagnetic near field. In addition, near-field plates can have a larger operating distance than conventional probes (electrically small apertures). The operating distance can be defined as the distance at which the subwavelength focus is formed. The electromagnetic field scattered or emitted by an electrically-small aperture diverges quickly away from it. In contrast, the highly oscillatory currents on a near-field plate confine the field and prevent it from diverging over a near-field focal length [9]. This allows a subwavelength focal spot to be maintained at a larger operating distance, or alternatively allows a smaller focal spot than could be achieved using a conventional probe at a fixed distance [11].

1. Aperture Fields Supported by a Near-Field Plate

To gain an understanding of near-field plates, as well as the near-field patterns they produce, let us consider one of the simplest near-field plates possible. A linear near-field plate is shown in Fig. 1, which can create a subwavelength line (1D) focus when excited by an electromagnetic source/incident wave. The depicted plate is invariant in the x direction, so the depicted geometry is two dimensional. For simplicity, let's consider the electric-field

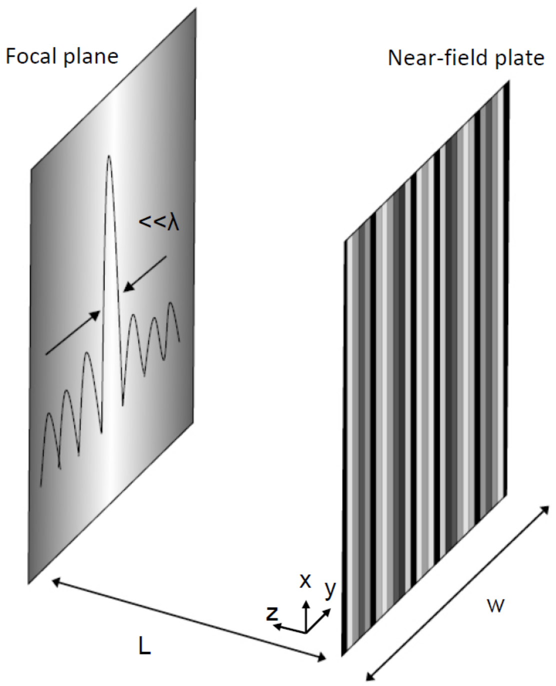


FIG. 1. A schematic showing a near-field plate ($z = 0$) and its focal plane ($z = L$). A near-field plate is a non-periodic, planar device that can focus electromagnetic field to spots or lines of arbitrary subwavelength dimension. The near-field plate's non-periodic impedance variation is graphically represented by its shading.

focus to be an s-polarized sinc function of the following form:

$$\vec{E}_{focal}(y, z = L) = E_0 \frac{\sin(q_0 y)}{q_0 y}\hat{x} = E_0 \mathrm{sinc}(q_0 y)\hat{x} \tag{1}$$

at a focal distance $z = L$ from the plate. The focus is plotted in Fig. 2(a) for a value of $q_0 = 10k_0$, where $k_0 = 2\pi/\lambda$ is the free space wavenumber. To find the general form of the aperture field (electric field at the surface of the near-field plate) needed to produce the subwavelength focus, we will simplify the problem and assume that the plate is infinite in extent ($W \to \infty$). By Fourier transforming the focal pattern, its spectral representation can be found

$$\vec{E}_{focal}(k_y) = E_0 \frac{\pi}{q_0} \Pi(k_y, q_\circ)\hat{x}, \tag{2}$$

where $\Pi(k_y, q_0)$ is the rectangular function with amplitude one, extending from $k_y = -q_0$ to $k_y = q_0$ in the spectral domain (see Fig. 2(b)). Back-propagating this spectrum (phase reversing the propagating spectrum and growing the evanescent spectrum from the focal plane to the plate's surface) and then inverse Fourier transforming (IFT) it, the aperture field at the surface of the plate can be obtained [10, 16],

$$\vec{E}_{ap}(y) = \mathcal{F}^{-1}\{\vec{E}_{ap}(k_y)\} =$$
$$\mathcal{F}^{-1}\{E_0 \frac{\pi}{q_0} e^{jk_z L} \Pi(k_y, q_0)\}\hat{x}, \tag{3}$$

(a)The subwavelength sinc focus given by (1).

(b)The spatial spectrum of the subwavelength sinc focus.

FIG. 2. The subwavelength sinc focus ($q_0 = 10k_0$) and its spectral representation.

where the symbol $\mathcal{F}^{-1}$ denotes the IFT with respect to transverse wavenumber k_y, and k_z is the wavenumber in the z direction defined as:

$$k_z = \begin{cases} \sqrt{{k_0}^2 - {k_y}^2} & : \quad {k_y}^2 < k_0^2 \\ -j\sqrt{{k_y}^2 - {k_0}^2} & : \quad {k_y}^2 > k_0^2 \end{cases}. \tag{4}$$

For near-field plates that focus electromagnetic waves to subwavelength resolutions ($q_0 \gg k_0$), the following quasi-static approximation can be applied [16]

$$\sqrt{k_0^2 - k_y^2} \approx -j|k_y| \tag{5}$$

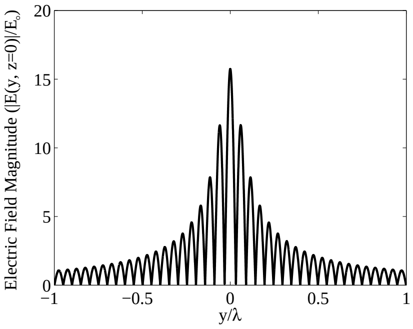
and the field at the plate simplified to the following approximate expression [10]

$$\vec{E}_{ap}(y) \approx \frac{E_0 e^{q_0 L}[L\cos(q_0 y) + y\sin(q_0 y)]}{q_0(y^2 + L^2)}\hat{x}. \tag{6}$$

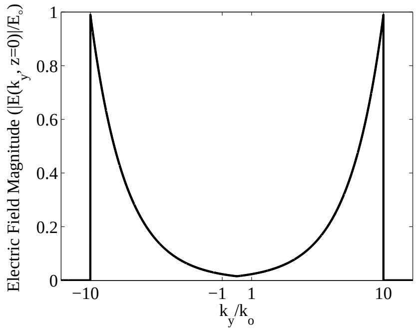
This field is highly oscillatory and has high evanescent field content. The aperture field needed to produce the focus shown in Fig. 2(a) is plotted in Fig. 3(a), where it is assumed that $L = \lambda/15$ and $q_0 = 10k_0$. The aperture field's spectrum is shown in Fig. 3(b), which clearly illustrates the dominance of the evanescent spectrum ($k_y > k_0$). Back-propagating the focal pattern from the focal plane to the plate's surface leads to an evanescent spectrum which exponentially increases with transverse wavenumber (k_y) [16]. In the quasi-static limit, the imaginary poles $\pm jL$ of the aperture field (see (6)) identify the near-field plate's focal length L [9]. In addition, the period of the highly oscillatory field along the plate (aperture field), characterized by the maximum wavenumber q_0, defines the resolution of the focus. For example, the null-to-null beamwidth of the focal pattern given by (1) is

$$\Delta y = \frac{2\pi}{q_0}. \tag{7}$$

These two properties of the aperture field, the imaginary poles which define the focal length and period of oscillation which determines resolution, are universal to all near-field plates [9].



(a)The aperture field given by (6).



(b)The spatial spectrum of the aperture field given by (6).

FIG. 3. The aperture field needed to produce the subwavelength focus shown in Fig. 2 and its spectral representation.

B. Work Performed and Accomplishments

This section summarizes the work that was performed under the Presidential Early Career Award for Scientists and Engineers (PECASE). The grant supported the development of a novel approach to subwavelength focusing using non-periodic, patterned surfaces. As noted, these patterned surfaces, referred to as near-field plates, were co-invented by the Principal Investigator (PI) and his collaborator, Roberto Merlin, at the University of Michigan. Roberto Merlin proposed a general class of aperture field distributions that can form a subwavelength focus at a prescribed focal plane in the aperture's reactive near field [9]. The PI's research group developed completely passive surfaces (near-field plates) that can achieve the desired aperture fields. In addition, the PI and his group outlined a detailed design procedure: explaining how to synthesize a near-field plate to produce a desired subwavelength focal pattern. Using this synthesis procedure, a number of prototypes were developed and experimentally verified. The advances achieved during the duration of the grant are outlined below. For a more in-depth description, the reader is referred to the Ph.D. dissertation of Dr. Mohammadreza F. Imani, the PI's former doctoral student [27].

1. Experimental Verification

Initially, the PI and his group devised a proof-of-concept near-field plate at microwave frequencies [10], and experimentally verified its ability to focus microwave radiation to subwavelength resolutions [11]. The near-field plate consisted of only capacitive elements and focused microwaves emanating from a cylindrical source to line focus (see Fig. 4). In experiment, a focus that is an eighteenth of a wavelength in size was formed by the plate. This focus is 6.5 times smaller than could be achieved using a conventional lens. Results of this initial study were reported in the journal Science [11].

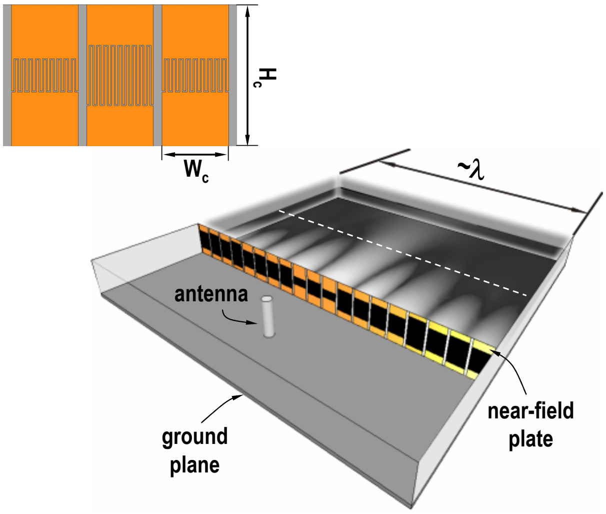


FIG. 4. Schematic showing the experimental set-up for testing the first near-field plate. The figure shows a dipole antenna (cylindrical source) and near-field plate inside a parallel plate waveguide. The top ground plane has been removed for clarity. The near-field plate consists of an array of interdigitated capacitors printed on an electrically-thin microwave substrate. Also shown is a contour plot of the electric field on the image side (logarithmic scale). The dashed white line denotes the focal plane. The three central interdigitated capacitors of the near-field plate are shown in the inset: $H_c = 15.0$ mm, $W_c = 7.5$ mm.

2. Analytical Investigation of Near-Field Plates

An analytical study of near-field plates by the PI's group provided insight into the design and operation of near-field plates [16]. The analysis highlighted the characteristic features of the current density and electromagnetic fields at the surface of near-field plates, and theoretically proved that these devices can be realized using purely reactive surfaces. It also showed how the electromagnetic fields change, both in the spatial and spectral domains, as they propagate from the plate's surface to the focal plane. These analytical results [16] were used to illustrate the similarities and differences between near-field plates and existing near-field focusing devices such as metamaterial slabs with negative material parameters.

3. Corrugated Near-Field Plates

Corrugated near-field plates were also developed as part of this research effort. In contrast to the initial design [11], which relied on illuminating sheets of printed circuit elements to create the desired focus, the new near-field plates relied on subwavelength grooves (corrugations) of varying depth which surround an central aperture to create the desired focus [13, 14, 21], as shown in Fig. 5. These new designs (referred to as "corrugated near-field plates") represent an important alternative to the patterned-surface near-field plates. The patterned-surface implementations were excited by a free-space wave, while the corrugated surfaces were directly fed by a coaxial waveguide, eliminating free-space path loss and improving the efficiency of coupling power from the source to the focus.

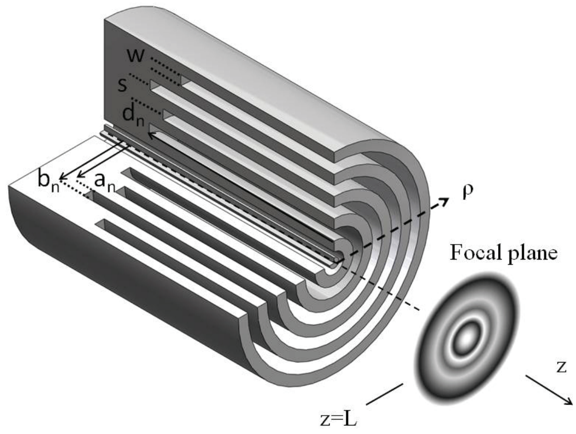


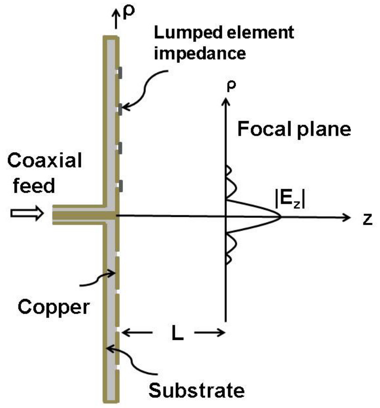
FIG. 5. A concentrically corrugated near-field plate. The focal spot is shown at a distance $z = L$ from the surface of the near-field plate

4. Near-Field Plates as High-Resolution Probes

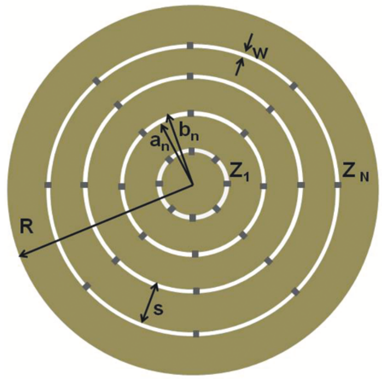
The experimental verification of a concentrically corrugated near-field plate constituted a major step forward in establishing the near-field plate concept as a practical means for tailoring near-field electromagnetics [21]. The developed near-field plate (see Fig. 5) was the first to produce a two-dimensional subwavelength focal pattern. The beam emitted by the corrugated near-field plate was significantly narrower than that emitted by the conventional coaxial probe, thus confirming the near-field plate's superior ability to confine electromagnetic field over a focal length (an extended operating distance). The corrugated near-field plate was used to image two coaxial sources placed a subwavelength distance apart. The images obtained using the near-field plate exhibited significantly higher resolution than those obtained using the coaxial probe alone [21]. The research results demonstrated that non-periodic, concentrically corrugated surfaces can provide new opportunities to develop high-resolution near-field probes and sensors.

5. Generating Bessel Beams with Near-Field Plates

Concentrically corrugated near-field plate which can generate evanescent Bessel beams at microwave frequencies were also developed [28]. The generation of evanescent Bessel beam was verified through full-wave simulation of the proposed near-field plate. The near-field plate consisted of nonperiodic concentric corrugations that surround a coaxially fed aperture. The performance of the near-field plate was contrasted against a coaxial probe and a near-field plate designed to produce an Airy focal pattern with the same beamwidth. In contrast to earlier methods of generating evanescent Bessel beams that were elaborate and bulky, and often only produced propagating Bessel beams, the near-field plate approach is straightforward and allows flexibility over the properties of the generated beam. For example, the inevitable truncation of Bessel beams can be tailored using the near-field plate approach [28]. The truncation of the Bessel beam has a significant impact on the beam performance: a wide truncation results in a beam that can retain its shape over a larger range, while a narrow truncation results in a short range. On the other hand, a smaller near-field plate is required to generate an evanescent Bessel beam truncated by a narrow truncation. We



(a)Side view



(b)Front view

FIG. 6. A planar near-field plate which consists of concentric annular slots on a circular grounded dielectric slab. The plate is excited through a coaxial cable and its rim is short circuited. The slots are loaded with lumped element impedances designed to produce a prescribed subwavelength focal pattern. (a) Side view. (b) Front view.

believe this simple and effective near-field plate approach to generating evanescent Bessel beams will find application in many areas such as near-field imaging/probing systems, high-resolution data storage, and medical targeting devices.

6. Planar Near-Field Plates

We have designed, fabricated, and measured planar near-field plates [29]. In contrast to earlier near-field plate designs, these surfaces can be directly fed through a connector and fabricated using standard printed circuit board technology. The plates consist of concentric annular slots on a circular grounded dielectric slab excited through a coaxial connector, as shown in Fig. 6. The annular slots are loaded with lumped element impedances which are designed to produce a prescribed subwavelength focal pattern.

A step-by-step procedure for designing these plates was introduced. Different near-field plates were designed to highlight the ability of near-field plates to produce various patterns. Two different near-field plates were designed to generate evanescent Bessel beams of different beamwidths, and a third one was designed to generate an Airy pattern. The proposed structures were fabricated using printed circuit board technology. The fabricated plates were shown to produce near-field patterns in close agreement with simulation, thereby experimentally verifying their design and operation. Furthermore, the Bessel beam near-field plates were experimentally demonstrated to produce a beam with nearly fixed shape and subwavelength beamwidth over a near-field distance. Over the same distance, neither the beamwidth nor the shape were preserved by the near-field plate that produced the Airy pattern.

The proposed near-field plates are planar, easy to fabricate and feed, and are robust to losses. Their planar design makes them amenable for integration with electronics. Given these promising characteristics, we believe these plates will emerge as practical means for tailoring the electromagnetic near field. They will find application in several areas such as high-resolution imaging and probing, biomedical targeting devices, as well as wireless power transfer devices.

7. *Unidirectional Near-Field Plates*

We developed a method for creating unidirectional, subwavelength electromagnetic near-field patterns [30]. Specifically, we devised near-field plates, which can form prescribed, unidirectional near-field patterns of subwavelength resolution. Earlier near-field plates demonstrated extreme field tailoring capabilities. However, their performance suffered from radiation/reflection into undesired directions; those other than the subwavelength focus. This hampered the performance of near-field plates, limiting their practical use. We addressed this long-standing issue by devising unidirectional near-field plates that can form a subwavelength focal pattern, while suppressing the field scattered/reflected in the backward direction. The design and operation of the unidirectional near-field plates was verified through full-wave simulation. Unidirectional near-field plates may find application in high-resolution imaging and probing, lithography systems, high-density data storage, electromagnetic targeting devices for biomedical applications, and wireless non-radiative power transfer systems. As an example, a unidirectional near-field plate's utility as a high-resolution probe was demonstrated through full-wave electromagnetic simulation.

8. *Near-Field Plates for Wireless Non-Radiative Power Transfer*

A near-field plate consisting of arrays of loops was developed for use in wireless non-radiative power transfer systems [31]. Specifically, a near-field plate was designed to replace the transmitting coil in current wireless non-radiative power transfer systems. The field emitted by coils in current systems form broad, dipole magnetic field patterns [32]. The goal was to develop near-field plates (arrays of subwavelength loops) that suppress radiation in unwanted directions and at far distances from the transmitter, while maintaining near-field coupling in the intended direction for high efficiency wireless power transmission.

We have demonstrated a highly efficient unidirectional wireless power transfer using near-field plates. The proposed near-field plate consisted of an array of loops placed close to the transmitting loop of a wireless power transfer system. The loops of the near-field plate were loaded with specified impedances to form a desired unidirectional near-field pattern. The step-by-step procedure to design such device was outlined. It was shown that the currents on the near-field plate can be adjusted such that the near-field plate and the transmitting loop interfere constructively in the forward direction (toward the receiver) and destructively in other directions, thus forming a unidirectional near-field pattern. Furthermore, the combined power leaked to the far field was reduced. Two different near-field plates were shown in fullwave simulation and experiment to be able to maintain a high power efficiency (comparable to existing technologies) while significantly suppressing the power leaked into unwanted directions. The proposed near-field plate can find application in many scientific, biomedical, security, and commercial devices to reduce health concerns, interference, and metering and detection problems.

C. Impact

Near-field probes and subwavelength focusing devices based on near-field plates, capable of generating subwavelength beam waists and focal patterns, will find numerous applications. Research on near-field plates may lead to advances in biomedical devices, microscopes with unprecedented resolution, lithography systems that allow unparalleled levels of electronic integration, as well as possible improvements to existing wireless power transfer systems.

The near-field plate's ability to manipulate the near field and provide strong spatial confinement could be leveraged to improve the performance of near-field sensors. High-resolution probes have already been developed for near-field microwave microscopy [13, 14, 21–23]. The subwavelength focus formed by a near-field plate when transmitting, allows it to detect over the same narrow spot when used as a receiver or probe. For microscopy applications, the availability of sub-micron and sub-nanometer feature fabrication techniques could allow arbitrarily high resolutions.

Near-field plates may also find use in wireless non-radiative power transfer systems. Specifically, megahertz receiving and transmitting devices based on near-field plates could provide specific advantages over the resonant coils that have been used to date [33]. Near-field plates could be designed to provide magnetic field illumination to only certain areas of a confined environment, where electronic devices are typically placed. For example, tailored "energy hotspots" could be established on the tops of desks or counter tops using near-field plates. Near-field plates may also radiate less energy to the far field than single or multi-turn loops due to the oscillatory (in and out-of-phase) currents supported by them.

Near-field plates could conceivably be used to improve targeting capabilities in medical devices such as those used in transcranial magnetic stimulation (TMS) [34]. Specifically, the use of near-field plates may lead to increased electromagnetic field penetration while still maintaining a small stimulated volume within the brain. In TMS, a time-varying magnetic field is used to induce an electromotive force within brain tissue in order to excite neurons. The super-resolving power of a near-field plate could perhaps be used to precisely direct neuronal stimulation in TMS.

At optical frequencies, near-field plates can be realized using plasmonic (inductive) and dielectric (capacitive) materials [35–40]. The microwave near-field plate designs reported could also be extended to optical frequencies using the concept of nanocircuit elements [41]. Nanostructured implementations hold promise for near-field optical data storage [42], near-field microscopy and lithography applications. Near-field plates could also be integrated into quasi-optical and optical systems as focusing or beam-shaping elements. For example, an incident beam could be focused to sub-wavelength spots (waists) prior to entering a millimeter-wave, THz, infrared or optical device. In this way, the size of system components could be significantly reduced. Such focusing elements could be used as light concentrators in infrared or optical detector arrays. Near-field plates could also be employed as beam-shaping devices. For instance, near-field plates have been used to generate Bessel beams.

III. CONTROLLING ELECTROMAGNETIC FIELDS WITH ANISOTROPIC AND INHOMOGENEOUS METAMATERIALS

A. Overview

This section covers research work related to the second research objective: arbitrarily controlling fields in a 2D space through electromagnetic anisotropy and inhomogeneity. This work began with the development of circuit-based metamaterials that exhibit tensorial effective material parameters, referred to as tensor transmission-line metamaterials. These metamaterials opened new opportunities in the development of planar transformation electromagnetics devices [43]. Homogenization methods were developed for tensor transmission-line metamaterials and they were used to realize a beam-shifting slab: a transformation electromagnetics device. The homogenization work resulted in methods to find alternative material parameters for transformation electromagnetics devices [43], and the development of synthesis methods for anisotropic and inhomogeneous media. These efforts are elaborated on in the following sections. For a more in-depth description, the reader is referred to the Ph.D. dissertation of Dr. Gurkan Gok, the PI's former doctoral student [44].

B. Work Performed and Accomplishments

This effort on arbitrarily controlling fields in a 2D space through electromagnetic anisotropy and inhomogeneity evolved over the course of this grant. The following subsections describe the work performed and contributions, in the sequence that they occurred.

1. Tensor Transmission-Line Metamaterials

The PI introduced tensor transmission-line metamaterials: a new class of metamaterials exhibiting tensorial effective material parameters, low losses and broad bandwidths of operation [45]. Tensor transmission-line metamaterials present a circuit-based approach to designing anisotropic and inhomogeneous media. They provide a one-to-one equivalence between material parameter tensors and circuit parameters, as shown in Fig. 7. In contrast to earlier works [4, 46–53], these transmission-line metamaterials can possess off-diagonal effective material parameters, while still maintaining a uniform rectangular unit cell. A circuit schematic of a tensor transmission-line metamaterial unit cell is shown in Fig. 8(a). A representative planar implementation of a tensor transmission-line unit cell is depicted in Fig. 8(b).

In this work, an approximate tensor analysis of the proposed metamaterials was developed. Bloch analysis was also carried out to verify the approximate analysis and derive exact dispersion equations and impedance relations. Finally, simulation results were presented that validated the analysis and showed the utility of this new class of metamaterials. The propagation characteristics of tensor transmission-line (TL) metamaterials were subsequently verified through full-wave analysis [54].The ability to design tensor metamaterials such as these is important to the practical implementation of novel devices derived through transformation optics/electromagnetics.

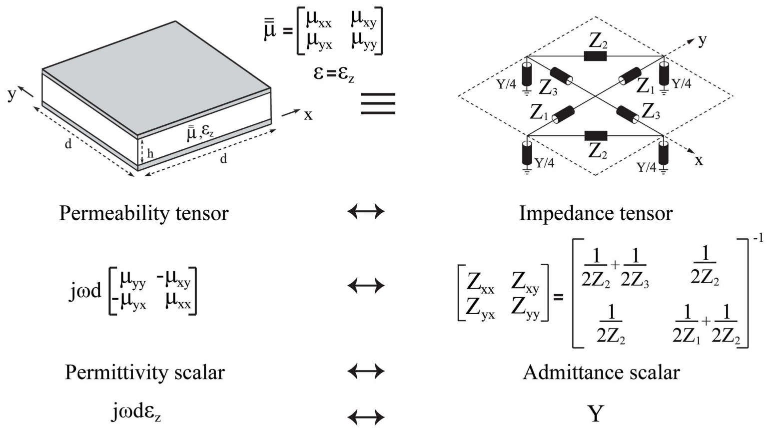


FIG. 7. The one-to-one relationship between material parameters of a magnetically anisotropic medium and the circuit quantities in tensor transmission-line metamaterials.

(a)Side view

(b)Front view

FIG. 8. Tensor transmission-line (TL) metamaterial unit cells (a) A circuit schematic of a tensor TL unit cell (b) A printed, tensor TL unit cell implemented using standard printed circuit board technology: printed traces over a grounded dielectric substrate.

2. Homogenization of Tensor Transmission-Line Metamaterials

After the introduction of tensor transmission-line metamaterials, a rigorous method for homogenizing these metamaterials was developed. Tensor transmission-line metamaterials consist of loaded transmission-line networks, that can possess magnetically anisotropic (tensor) effective material parameters. The developed homogenization employs a local field averaging procedure to compute the anisotropic effective material parameters. The material parameters can be dispersive or non-dispersive. For the tensor metamaterials possessing dispersive effective material parameters, the homogenization method takes advantage of the circuit topology of tensor transmission-line metamaterials to predict material parameters over a frequency range. The developed homogenization method was essential to characterizing and designing tensor transmission-line metamaterials that can be fabricated using standard printed circuit board techniques, and used to design planar transformation electromagnetics microwave devices.

3. Alternative Material Parameters for Transformation Electromagnetics Designs

The development of the homogenization process for tensor transmission-line metamaterials inadvertently led to a second discovery: a formulation for finding alternative material parameters for 2-D transformation electromagnetics (inhomogeneous, anisotropic) devices [55]. The alternative material parameters support exactly the same field pattern as the original ones of the transformation electromagnetics device. The same method was also extended to design dual functional transformation electromagnetics devices that combine the characteristics of two separate transformation devices into one. An analytical formulation was shown in [55] and the results were verified through the full-wave simulation of well-known transformation electromagnetics devices: an electromagnetic field rotator and a cylindrical electromagnetic field concentrator. Although the transformation electromagnetics devices possessing alternative material parameters only work for a particular illumination direction, the method presented will find application in the design of antennas and beam-forming networks with a fixed feed position.

4. A Transformation-Designed Device Implemented with Tensor Transmission-Line Metamaterials

To demonstrate the utility of tensor transmission-line metamaterials in implementing devices with anisotropic and inhomogeneous material parameters, a planar transformation electromagnetics device was implemented [56]. A beam-shifting slab (a transformation electromagnetics device) was implemented using tensor transmission-line metamaterials. A photograph of the device is shown in Fig. 9. A beam-shifting slab is an anisotropic, homogeneous and reflectionless slab which laterally displaces the electromagnetic field transmitted through it. The experimental beam-shifting slab consists of printed tensor transmission-line unit cells exhibiting anisotropic effective material parameters, while the surrounding medium consists of printed isotropic unit cells. The measured and simulated field patterns within the beam-shifting slab and the surrounding media were compared and showed excellent agreement. Simulation and experimental results demonstrated that radiation from a cylindrical source is shifted upward by 5.28 unit cells due to the presence of the beam-shifting slab. Furthermore, the wide-band frequency response of the slab was experimentally studied.

The reported results experimentally verified the theory behind tensor transmission-line metamaterials and demonstrated their utility in the design of transformation electromagnetics devices at microwave frequencies. They showed how tensor TL metamaterials have enabled the design and implementation of transformation electromagnetics devices using circuit networks.

5. Tailoring the Phase and Power Flow of Electromagnetic Fields with Metamaterials

The formulation for finding alternative material parameters for transformation electromagnetics devices motivated further work. It lead to the development of a method for arbitrarily controlling the phase progression and power flow of electromagnetic fields within a 2D region of space [57]. The formulation describes how a 2D inhomogeneous, anisotropic medium can be designed that supports desired spatial distributions of the wave vector and Poynting vector direction. Plane-wave relations in anisotropic media were used in conjunc-

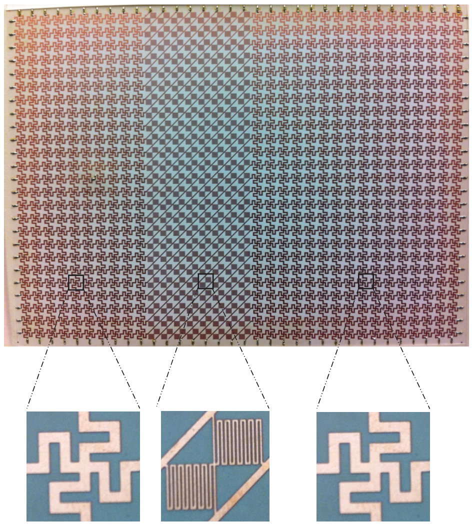


FIG. 9. The experimental structure showing the printed beamshifting slab (consisting of anisotropic unit cells) surrounded by a medium (consisting of isotropic unit cells). The structure was fabricated using standard printed circuit board fabrication processes. The corresponding anisotropic (center) and isotropic unit cells (on each side) are shown in the inset.

tion with an impedance matching process to find the required material parameters. The proposed design approach provides independent spatial control of phase progression and power flow. Such control allows one to independently tailor the phase and amplitude of a field profile. It could find use in the design of a wide range of electromagnetic devices including antennas and beam-forming networks, and may also find application in scattering control and holography. Figure 10 shows a 2D inhomogeneous, anisotropic region that was designed using the proposed approach. It converts an incident cylindrical wave at boundary 1 to a field profile with a triangular power density distribution and uniform phase at boundary 2.

C. Impact

The proposed design approach provides independent spatial control of the phase progression and power flow of electromagnetic waves within a 2D medium. This control can be extended to surfaces through the use of tensor transmission-line metamaterials. The design approach will find use in the development of a wide range of electromagnetic devices including antennas and beam-forming networks, and may also find application in scattering control [58, 59] and holography [60, 61]. It could provide a novel approach to signal routing, the design of mode conversion devices [62], and the generation of extreme antenna apertures for super-directive radiation [63] or the excitation of Airy [64–67] and Bessel beams [68–71]. For example, in antenna design, one may wish to control power flow across an aperture in order to realize a given amplitude distribution (beam shape), while at the same time control phase progression to establish a certain beam-pointing direction. In the case of a beam-former, one may wish to stipulate an input field distribution (excitation) and an output field distribution (amplitude and phase distribution of the antenna elements), with a transition from one to the other. Therefore, spatial control of phase and power flow also

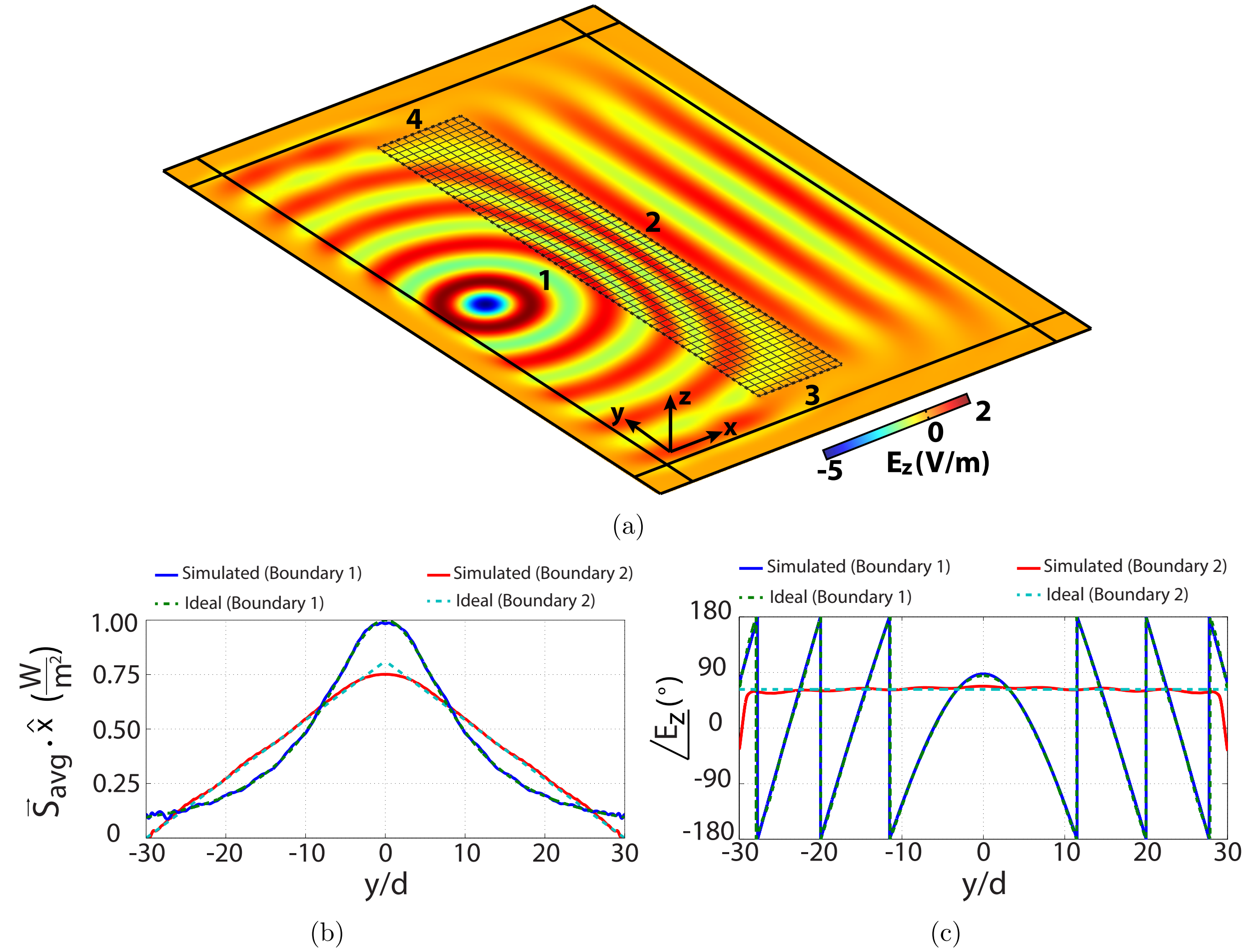


FIG. 10. (color online). (a) Time snapshot of the simulated, vertical electric field (E_z) within an surrounding the designed 2D inhomogeneous, anisotropic region. (b) Simulated and ideal power densities along boundary 1 and boundary 2. (c) Phase profiles along boundary 1 and boundary 2.

allows one to independently mold the phase and amplitude of a field profile.

Earlier works have attempted to control these two quantities through coordinate transformations. Finite embedded coordinate transformation method introduced in [72] was used to laterally displace the power flow of an Gaussian beam while preserving its phase progression. On the other hand, [73] showed how to control the phase-front of a beam while retaining its power flow direction. Here, we demonstrate simultaneous control over both the phase progression and power flow of electromagnetic fields without defining a coordinate transformation.

IV. PERSONNEL SUPPORTED

The following people were supported by this research effort:

- PI: Anthony Grbic.
- Graduate Students: Scott Rudolph, Mohammadreza F. Imani, Amit Patel, Gurkan Gok, Carl Pfeiffer, Lai Wei, Brian Tierney, Adam Weiss, and Nikolaos Chiotellis.

- Postdoctoral Researcher: Francis Elek.
- Visiting Scholar: Mauro Ettorre.
- Summer Undergraduate Researchers: Tony Chen, Brett Kuprel, and Dike Zhou.

V. PUBLICATIONS

Publications stemming from this research effort are listed below.

A. Journal Papers

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